Technical Report Documentation Page

1. REPORT No.
CA-HWY-MR633296(2)-72-17

2. GOVERNMENT ACCESSION No.

3. RECIPIENT'S CATALOG No.

4. TITLE AND SUBTITLE
Design Of Lime Content And Field Control Limits For Soil Stabilization; Final Report

5. REPORT DATE
March 1972

6. PERFORMING ORGANIZATION

7. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT No.
CA-HWY-MR633296(2)-72-17

9. PERFORMING ORGANIZATION NAME AND ADDRESS

10. WORK UNIT No.

11. CONTRACT OR GRANT No.
D-4-63

12. SPONSORING AGENCY NAME AND ADDRESS

13. TYPE OF REPORT & PERIOD COVERED
Final Report

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
This work was done in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

Construction control data from nineteen California State Highway contracts was obtained and statistically analyzed to determine the magnitude and uniformity of the percentage of lime added to the basement soil. The lime contents were determined using the California titration test. The data from projects constructed with the most efficient mixing machine were used to develop recommendations for new specifications for lime content. These new statistical type specifications have been recommended for implementation by the California Division of Highways in lieu of the existing absolute specification requirement for lime content.

17. KEYWORDS
Construction equipment, efficiency, lime treatment, mixers, specifications, stabilization, statistical analysis, tests

18. No. OF PAGES:
28

19. DRI WEBSITE LINK
http://www.dot.ca.gov/hq/research/researchreports/1972/72-17.pdf

20. FILE NAME
72-17.pdf

HIGHWAY RESEARCH REPORT

DESIGN OF LIME CONTENT AND FIELD CONTROL LIMITS FOR SOIL STABILIZATION

FINAL REPORT

STATE OF CALIFORNIA

BUSINESS AND TRANSPORTATION AGENCY

DEPARTMENT OF PUBLIC WORKS

DIVISION OF HIGHWAYS

MATERIALS AND RESEARCH DEPARTMENT

RESEARCH REPORT

CA-HWY-MR633296(2)-72-17

Prepared in Cooperation with the U.S. Department of Transportation, Federal Highway Administration March, 1972

STATE OF CALIFORNIA—TRANSPORTATION AGENCY

RONALD REAGAN, Governor

DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS
MATERIALS AND RESEARCH DEPARTMENT
5900 FOLSOM BLVD., SACRAMENTO 95819

Final Report
FHWA No. D-4-63
M&R No. 633296

March 1972

Mr. R. J. Datel
State Highway Engineer

Dear Sir:

Submitted herewith is a final research report titled:

DESIGN OF LIME CONTENT AND

FIELD CONTROL LIMITS

FOR SOIL STABILIZATION

George B. Sherman
Principal Investigator

Robert D. Hamilton - Robert E. Smith
Analysis and Report

Very truly yours,

JOHN L. BEATON
Materials and Research Engineer

REFERENCE: Hamilton, R. D., Smith, R. E., and Sherman, G. B., "Design of Lime Content and Field Control Limits For Soil Stabilization," State of California, Department of Public Works, Division of Highways, Materials and Research Department, Research Report CA-Hwy-MR 633296(2)-72-17, March, 1972.

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ACKNOWLEDGMENTS

The authors wish to express their appreciation to the construction and materials personnel of Districts 03 and 10 of the California Division of Highways for their assistance in obtaining much of the data for this investigation.

This work was done in cooperation with the U. S. Department of Transportation, Federal Highway Administration, and their contribution is hereby acknowledged. The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Federal Highway Administration.

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BACKGROUND AND INTRODUCTION

Since 1966, California's Specifications (1) for lime stabilization on state highway projects have not been restrictive on the type of mixing equipment used. This has resulted in the widespread use of "rotary" mixers. These rotary mixers have one or more transverse shafts that cut and mix in-place material on the grade. The various manufacturers of these machines claim that a consistently uniform mixture of soil-lime or soil-cement can be obtained. Self-propelled pugmill-type mixers have been used on some lime treatment projects also, but usually the rotary-type mixers are selected by contractors for reasons of economy and higher production rates.

This research project was initiated in July 1966. The objectives were to: 1.) investigate the efficiency of various brands of spreading and mixing equipment, 2.) determine methods to improve construction procedures and encourage improved equipment designs, and 3.) develop necessary data for the preparation of realistic and enforceable specifications for control of the quality of lime stabilization by road mixing methods.

An interim report (2) on this research project was completed in February, 1970. That report essentially covered the first two research objectives cited above. It included results of field tests on two brands of lime spreaders, three brands of rotary-type mixers, and two brands of pugmill mixers. Consideration was given to evaluating additional machinery used on some state highway projects. However, it was concluded that design features of these machines were not significantly different from those already investigated, and, consequently, the field investigation was not pursued further.

The interim report contains the following important findings:

1. The lime spreading equipment studied was not capable of consistently spreading lime within California's current specification limits. Those required that "the rate of lime spread per linear foot of windrow or blanket shall not vary more than 10 percent from the designated rate." This requirement was only met in 24 percent of the check tests on the <u>better</u> spreader.

2. None of the mixers tested gave a consistently uniform blend of lime-soil mixture. Specifications require that "the lime content of samples taken...shall not have a variation above or below the lime content (percent by dry weight) designated by the Engineer of more than one percent...." The <u>best</u> equipment tested showed about 73 percent passing tests.

The interim report explained that nonuniformity of the completed mixture resulted from:

1. Uneven spreading of the lime and inability of the mixers to redistribute the lime uniformly, particularly in the transverse direction.

2. Failure of the rotary type mixers in maintaining uniform depth control.

Various suggestions were made to improve equipment design and construction procedures. The interim report also recommended that more realistic and enforceable specifications be developed. In order to develop these specifications, it is necessary to have factual information as to the distribution of lime on representative projects. From this data, the variance (or standard deviation) can be selected that represents what can be reasonably obtained using the best available equipment and techniques.

The data collected for the interim report were experimental in nature. It was not considered completely representative of actual construction test data, obtained under a wide variety of conditions. Additional funds were requested and approved to compile construction control data from the contract records of numerous lime projects, analyze the data, and develop new specifications. It is important to emphasize that this supplementary research was directed toward the development of these improved specifications rather than toward an analytical study of the relative efficiency of various types of mixing and spreading equipment. The purpose of this final report, then, is to present the results of this additional work program and to recommend new specification limits for the lime content.

Data were collected with the assistance of personnel in Districts 03 and 10. A total of nineteen state highway projects, all completed since 1965, were included in the study.[1] The projects involved a wide variety of construction equipment[1] and various soil conditions. The test results for lime content were then analyzed to develop appropriate limits for statistical type specifications.

[1] A partial list of equipment used is listed in the appendix. In many cases, the data studied did not provide the complete model designation, or reflect condition of machinery or any modifications which may have been made.

CONCLUSIONS AND RECOMMENDATIONS

1. The best control of lime distribution achieved only about 70 percent conformance with existing specifications for lime content. Poorest distribution of lime resulted in about 50 percent conformance in those projects studied.

2. For existing spreading and mixing equipment, California's absolute-type specifications (1, 1971) for lime content are judged to be overly restrictive and impractical if literally enforced.

3. It is concluded that statistical data obtained in this research for the more efficient equipment may be used to develop improved means for design and control of lime treatment. This should result in:

   a. An improved method of establishing the contracted lime content.

   b. A more rational criteria for acceptance or rejection of material, with realistic and enforceable limits.

   c. Greater uniformity in specification interpretation and enforcement.

   d. The continued development of improved equipment and construction methods.

4. It is recommended that the percentage of lime (X) specified in a contract be such that 90% of the project can be expected to have a lime content greater than a minimum design percentage (x') determined on the basis of laboratory testing. Based on the average variance found for the better equipment studied in this research, an additonal 1.3 percent of lime is required to insure this minimum distribution:

$$X = x' + 1.3\%$$

5. It is recommended that the field control limits be established for a control test and running average as follows:

   a. A control test for material being considered for compliance with specifications should be the mean of four individual tests: $\bar{x}_{(4)}$

   The minimum percentage should be $X - 0.8\%$.

COMPILATION OF DATA

Construction control data were compiled from nineteen state highway projects that required lime treatment. Located in Districts 03 and 10, all of these projects were completed since 1965. Six different manufactured brands of road-mixing machines were used, five of these being rotary types and one a pugmill type. These six machines were selected as it was believed that they represented the range in significant mechanical differences between most models used during this time.

All measurements of lime content were obtained during construction by the various project personnel. Samples were taken from the roadway after mixing. Lime contents of the samples were determined by the titration test (3, Test Method No. Calif. 338). In cases where resampling was performed at any test station[1], only the final test results were used in this study. These data, then, essentially represent the accepted lime distribution on each project.

At the outset of the data collection program it was assumed that construction records would provide information on the rate of spread of lime. However, sufficient information was not available to permit a study of the independent contributions of the lime spreading and mixing equipment to the total variance of indicated lime content. Consequently, the results of titration tests for lime content that were performed on the completed mixture are indicative of the combined efficiencies of the mixer and spreader used on each project.

The planned or contracted lime contents for the nineteen projects varied from 3.0 to 4.5 percent by weight of the dry soil. Some projects required more than one design lime content, due to different soil types throughout the contract length. As a result, twenty-six test areas were obtained from the nineteen projects.

INDICATED LIME DISTRIBUTION

Table 1 summarizes the data collected for the various equipment and presents the indicated lime distribution in statistical terms.

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[1]The data were taken in sets of two or four individual tests at each test station.

TABLE 1

INDICATED LIME DISTRIBUTION

Mixer Brand	Mixer Type	No. of Projects or Areas Studied	Planned (contracted) Percent Lime	No. of Individual Tests (n)	Indicated Percent Lime (Mean) ($\bar{X}$)	Variation of mean from Planned Percent Lime	Standard Deviation from Mean (σ)	Range in Test Values (R)
A	Rotary	1 5 5	3.50 4.00 4.50	60 120 168	3.47 3.86 4.47	-.03 -.14 -.03	0.84 1.25 0.90	3.90 6.30 4.90
B	Rotary	1 2	3.00 4.00	56 84	3.12 4.03	+.12 +.03	0.70 1.46	2.60 9.10
C	Rotary	2 1	4.00 4.50	40 14	3.48 4.99	-.52 +.49	1.14 1.58	4.00 5.30
D	Rotary	2	4.00	46	3.92	-.08	1.53	6.20
E	Rotary	1 1 1	3.50 4.00 4.50	19 68 76	3.44 4.44 5.01	-.06 +.44 +.51	1.26 1.28 1.21	5.00 6.30 6.10
F	Pugmill	1 2 1	3.00 4.00 4.50	36 84 18	4.00 4.01 4.47	+1.00 +.01 -.03	1.28 1.22 0.49	4.60 5.60 1.60

To explain the information presented in this table, let us refer to the first line of data tabulated for Mixer "A" as an example: Sixty individual tests were taken from one project where the planned or contracted lime content was 3.50 percent. The mean indicated lime content of these 60 tests was 3.47 percent, with a standard deviation from the mean of 0.84 percent lime. The range of test results from the lowest to highest lime content was 3.90 percent.

The remaining lines of data shown in Table 1 were similarly obtained to reveal the distribution of lime for each mixer at varying contracted lime contents. In general, the results indicate that a wide variation in uniformity of mixing exists within and between each mixer grouping. Although in many cases the overall average lime contents ($\bar{X}$) were close to the amounts specified, distribution of lime was not maintained within current specification limits (i.e., within ± one percent of the contracted lime content).

It should be realized that, in spite of the apparent non-compliance with specifications, these data represent what has been considered to be acceptable standards of work. The so-called "failing tests" are those which would be normally expected on the basis of the observed variances and probability theory. These have been accommodated in the past by the practice of retesting and the acceptance of a certain number of failing tests. This process is discussed in the report "A Statistical Analysis of Embankment Compaction" (4). (Although this report is concerned with density measurements, the developed arguments are analogous to lime content tests.)

In only one of the projects included in this study, 100 percent of the final tests complied with existing specifications for lime content. This occurred for Mixer "F" where 18 samples were tested and the planned lime content was 4.50 percent. However, this indicated excellent distribution is believed to be not truly indicative of Mixer "F" efficiency because of:

1. The small number of tests (n = 18).

2. A much less uniform distribution of lime by the same mixer for the projects with 3.0 and 4.0 percent contracted lime.

EQUIPMENT PERFORMANCE

The data presented in Table 2 provide an overall estimate of equipment performance. Essentially, this table is a condensed summary of the data presented in Table 1. Weighted average values of standard deviation for the individual mixers have been calculated to show the relative overall performance of each brand of mixer. A typical calculation for the weighted average value of the standard deviation $\bar{\sigma}_{(1)}$ for Mixer "A" is shown at the bottom of Table 2.

Best overall lime distribution was obtained on projects where Mixer "A", a rotary-type mixer, was used. From all of the individual tests for this mixer, the calculated value of one standard deviation is 1.01 percent lime. Table 2 shows that 69 percent of the individual tests were within current specification tolerances. Seventeen percent of the tests failed the <u>minimum</u> lime content requirement.

At the other extreme, poorest lime distribution was indicated by the data obtained for Mixer "D", another rotary-type machine. The weighted standard deviation of the titration test results was 1.53. Only 49 percent of the tests met existing specifications with 27 percent deficient of the minimum permitted.

Mixer "F", the only pugmill-type mixer included in this study, was found to rate somewhere in efficiency between the best and worst rotary-type mixer.

TABLE 2

COMPARISON OF EQUIPMENT

Mixer	Total Number of Tests	Weighted Standard Deviation of Individual Tests from Average $\bar{\sigma}_{(1)}$	% of Individual Tests Meeting 1971 Specifications	% of Tests Failing Minimum Lime Content by 1971 Specifications
		Overall Equipment Performance Based on Weighted Average Values for Data Shown in Table 1		
A	348	1.01*	69	17
B	140	1.16	64	11
C	54	1.26	54	29
D	46	1.53	49	27
E	163	1.25	55	13
F	138	1.15	58	15

* Sample Calculation

From the data shown for Mixer "A" in Table 1, the weighted average standard deviation =

$$\frac{(60 \times 0.84) + (120 \times 1.25) + (168 \times 0.90)}{60 + 120 + 168} = 1.01$$

EFFECT OF DATA VARIANCE ON DESIGN AND SPECIFICATIONS

As has been previously discussed, these so called "failing tests" are always present when absolute-limit type specifications are employed. A certain percentage of these will occur on fully acceptable construction unless limits are set so wide as to provide, in effect, no control at all. The problem with the absolute-limit type specification is that no standards are provided for legitimately accommodating those tests which fall below the given limit. As a result, nonuniformity occurs in the interpretation and enforcement of the specification. Consequently, the acquired data was further analyzed to provide a more rational basis for field control of lime content.

Another object of the evaluation was to develop an improved procedure for determining the design or "pay" lime content itself. In the past this has been done without consideration of the combined variances involved in mixing lime with soil. However, the design procedure should recognize that the best that can be expected is what can be produced with good techniques using the better equipment. Therefore, if we contract for say 4.0 percent lime, and the best mixing operation has a standard deviation in order of 1.0 percent, it is to be expected that approximately 16 percent of the project has a lime content below 3 percent. It is unrealistic to expect a contractor to provide an excess of lime to reduce this percentage, no matter what the nominal specification limits are.

It is therefore considered more satisfactory to make an engineering decision such as, "at least 90 percent of the project should have a lime content above some minimum percentage." Then, the contract percentage of lime is determined based on a recognition of the current capabilities of the equipment and methods available.

A suggested procedure for specifying lime content and field control limits follows.

DEVELOPMENT OF DESIGN AND SPECIFICATION CRITERIA

The current trend in California Highway specifications is to use the average or mean of a small sample of size (n) as a basis for decision. This practice has been implemented for many test procedures, such as the Ball Penetration Test (3, Test Method No. Calif. 533).

In order to do this for lime content, it is necessary that the variance of the small sample means $\sigma_{(n)}$ be known or estimated.

Since most of the data was acquired in sets of two or four individual tests, the set means $\bar{x}$ were calculated. Then the standard deviations of these set means about the grand mean $\bar{X}$ were computed for Mixer "A". These are designated in Table 3 as the observed standard deviations of the sample means.

Also included in Table 3 is an estimate of the expected standard deviation of sample means. This is approximately equal to:

$$\sigma_{(n)} = \frac{\sigma_{(1)}}{\sqrt{(n)}}$$

where (n) is the sample size.[1]

It is seen that the expected standard deviations of sample means for planned lime contents of 3.5 and 4.5 percents are in good agreement with those experimentally determined. At a planned lime content of 4.0 percent, the agreement is not as satisfactory. This was found to be due to a nonuniform distribution of data. It was concluded that the standard deviation of small sample means could be satisfactorily estimated on the basis of equation [1]

<u>Setting Contracted Lime Content</u>

The design or contracted lime content (X) may be calculated by the following equation:

$$X = x' + z_{(90)} \cdot \sigma_{(1)}$$

where x' is the minimum desirable lime content as determined by laboratory tests. The quantity $z_{(90)}$ is the "z-score" index, or the multiple of the standard deviation of individual test values $\sigma_{(1)}$, which is expected to include 90 percent of normally distributed data[2].

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[1]Sampling with replacement is assumed for purposes of this estimate.

[2]A one-tailed test applies because we specify only a minimum contracted lime content.

TABLE 3

EXPECTED AND OBSERVED STANDARD DEVIATIONS FOR CONTROL TESTS

-MIXER A-

Planned Lime Content	Sample Size (n)	Number of Sets (N)	Observed Standard Deviation of Individual Tests $\sigma_{(1)}$	Observed Standard Deviation of Sample Means $\sigma_{(n)}$	Expected Standard Deviation of Sample Means $\frac{\sigma_{(1)}}{\sqrt{(n)}}$ *
3.5	2	28	- -	.53	.60
	1	60	.84	- -	- -
4.0	4	26	- -	1.05	.63
	2	8	- -	1.26	.89
	1	120	1.25	- -	- -
4.5	4	17	- -	.43	.45
	2	49	- -	.77	.64
	1	168	.90	- -	- -

* $\sigma_{(1)}$ = observed standard deviation of individual tests

The following example illustrates the procedure for setting the contract lime content. Recalling that the weighted standard deviation for Mixture A (Table 2) was 1.0% lime, assume that laboratory tests indicate the minimum desirable lime content for a particular soil is 2.7% lime. Then:

$$\begin{aligned} X &= 2.7 + z_{(90)} \cdot \sigma_{(1)} \\ &= 2.7 + (1.3)(1.0) \\ &= 4.0 \text{ \% lime} \end{aligned}$$

Specification Limits

Equation [3] may be used to set limits for field control tests, and the moving average. The expected standard deviation of control test means $\sigma_{(n)}$ is estimated on the basis of equation [1].

Then:

$$\bar{x}_{(n)} \geqq X - t_{(90)(v)} \cdot \frac{\sigma_{(1)}}{\sqrt{(n)}} \qquad [3]$$

Here, $t_{(90)(v)}$ is the "Student's t" distribution index for the 90 percent expectation, and $v = (n-1)$ degrees of freedom. This is analogous to the z-score, except that the comparable limits are wider due to uncertainties introduced by the small sample size.

For our example, and using a recommended sample size of $n=4$ to represent a "lot" of material, the minimum specification limit for the test result is:

$$\begin{aligned} \bar{x}_{(4)} &\geqq X - t_{(90)(v=3)} \cdot \frac{\sigma_{(1)}}{\sqrt{4}} \\ &\geqq 4.0 - (1.64 \cdot \frac{1.0}{2}) \\ &\geqq 4.0 - 0.8 \\ &\geqq 3.2 \text{ \% lime} \end{aligned}$$

Similarily, the minimum lime content for the moving average with a sample size of 20, (i.e. five control test results) is:

$$\bar{x}_{(20)} \geqq X - t_{(90)(v=19)} \cdot \frac{\sigma_{(1)}}{\sqrt{20}}$$

$$\geqq 4.0 - (1.33 \cdot \frac{1.0}{4.46})$$

$$\geqq 4.0 - 0.3$$

$$\geqq 3.7\ \%\ \text{lime}$$

Closing Remarks

The values given by equations [2] and [3] are directly influenced by the variance in lime distribution as determined by equipment efficiency and construction techniques. For the nineteen projects included in this research, the standard deviation $\sigma_{(1)}$ of 1.0 percent is indicative of the best lime distribution studied. However, new types of machinery for spreading and mixing lime are being developed rapidly as the volume of lime treatment for highway construction increases. Consequently, periodic reevaluation of the combined variances in lime distribution will be necessary to adjust specification limits commensurate with the improvement of construction equipment and techniques.

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1. State of California, Department of Public Works, Division of Highways, Standard Specifications, 1969 and 1971.

2. Zube, E., Gates, C. G., and Matthews, J. A., "Investigation of Machines Used for Road Mixing," February, 1970.

3. State of California, Department of Public Works, Division of Highways, Materials Manual.

4. Sherman, G. B., Watkins, R. O., and Prysock, R. H., "A Statistical Analysis of Embankment Compaction," (presented at the 46th Annual Meeting of the Highway Research Board, January, 1967).

APPENDIX

EQUIPMENT STUDIED

Designation	Mixer	Spreader
A	Koehring - 4 shaft	Universal
B	Koehring - single shaft	(unknown)
C	Seamon	Brown
D	Metradon	(unknown)
E	Rex	Auger from truck
F	Pettibone Wood-pugmill	Truck with screw feed into windrow.